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CRREL's *Cold Regions Technical Digests* are aimed at communicating essential technical information in condensed form to researchers, engineers, technicians, public officials and others. They convey up-to-date knowledge concerning technical problems unique to cold regions. Attention is paid to the degree of detail necessary to meet the needs of the intended audience. References to background information are included for the specialist.

COLD REGIONS TECHNICAL DIGEST No. 85-1, JULY 1985

USA Cold Regions Research and Engineering Laboratory
Hanover, New Hampshire 03755

Radar profiling of ice thickness

Steven A. Arcone

Introduction

Large-scale profiling of the thickness of freshwater and sea ice is important for understanding the dynamics of a sea ice cover, interpreting satellite microwave imagery, and predicting air-sea heat exchange or the bearing capacity of an ice cover. A practical approach to thickness sensing would be to use a remote ranging system that sends and receives a pulse of energy that reflects from the bottom of the ice. The time of flight of the pulse would then be calibrated to ice thickness. Acoustic (sonar) systems are not well suited because sound couples inefficiently from air to solids. Resolution would thus be poor unless ultrasonic frequencies were used, in which case too much sound energy would scatter in all directions from ice cracks. Electromagnetic (EM or radiowave) systems are better suited because the energy does couple well from air into non-conducting solids such as ice. Additionally, EM pulses can be made short enough for good resolution without worrying about scattering.

In the late 1960s radar systems were designed that were capable of probing below the ground surface with extremely short bursts of energy. Commercial systems, known usually as ground-probing impulse radars, may obtain geological information to depths of up to 10 m in some soils, up to 15 m in fresh water, and up to at least 100 m in good dielectric insulators such as glacial ice. A dielectric insulator like glass, plas-

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tic or ice does not conduct electricity but does let waves propagate. Conductive materials like metal, salt water and wet clay convert wave energy into electric currents and are therefore highly absorbing.

As with many other geophysical exploration systems, radar data are interpreted most easily where the ground is composed of even, flat layers. Consequently, radar can provide an excellent (although sometimes boring) profile of ice thickness. Where layering breaks up, radar data can be extremely complicated. But if the spatial length of the energy burst is about the same size as or smaller than the radius of curvature of the subsurface unevenness, chances are excellent that the impulse radar echoes will track the irregularities with good precision.

The subsurface radar system

This section describes the important aspects of subsurface radar without resorting to any mathematical complexities of electromagnetic wave propagation and signal processing. To facilitate the description, comparisons will be made with conventional surface radar, used primarily for tracking airborne objects.

In both radars, EM energy is transmitted in bursts and echoes are received from reflecting objects, allowing their detection. As with all waves in nature the velocity v is related to the frequency f and the wavelength L by

$$v = fL.$$

For all EM waves (radio, infrared, light, X-rays) v in space is always 3×10^8 metres/second. Conventional radars (Fig. 1) transmit bursts (pulses) of microwave energy at frequencies between 1 and 10 GHz (1 GHz = 1 billion cycles per second) so that their wavelengths are very short (3–30 cm). However, the pulse usually lasts between 0.1 and 1 millionth of a second (μs), so that the whole pulse is between 30 and 300 m long as it travels through space. This length is unacceptable for ice profiling because the pulses would overlap each other as they partially reflect from the top and bottom of the ice, thus giving one long blurry echo from two distinct reflectors.

In ground-probing radar (Fig. 2), the pulse lasts only about 1 to 10 billionths of a second (ns), and is therefore about 30 to 300 cm long. This is still a bit long for most ice covers, but there is an additional effect. In a material, the velocity v_m is slowed down by the index of refraction n such that

$$v_m = c/n.$$

This effect makes the pulses shorter in space by the same factor n. Freshwater ice has an n of about 1.8, shortening subsurface pulses to between 15 and 150 cm. The low end of this range is now short enough to prevent the front of a pulse reflecting off of an ice bottom from overlapping the back of a pulse reflecting off of an ice surface.

With conventional radar, targets (e.g. planes, boats) are usually far enough away to allow the same antenna to both transmit and receive without having echoes interfere with transmissions. The antenna is usually a large, parabolic-shaped dish capable of propagating a narrow, shaped beam in very precise directions. This is afforded by the very high carrier frequency of the transmissions and the fact that essentially only one frequency is transmitted. In ground radar, the transmit and receive antennas are kept separate so that extremely close reflectors can be detected without worrying about echoes coming back into the transmitter while it is still transmitting. Subsurface shaped-beam antennas are not (yet!) possible because shaping the pulse in time is a higher priority. Consequently, wave energy is transmitted over a large solid angle, and unwanted side echoes may cause problems. Fortunately, such is not usually the case with flat, homogeneous ice, although there are exceptions, which we will see later.

The range R of a target is determined by the time delay t of an echo. The relationship for conventional radars is simply

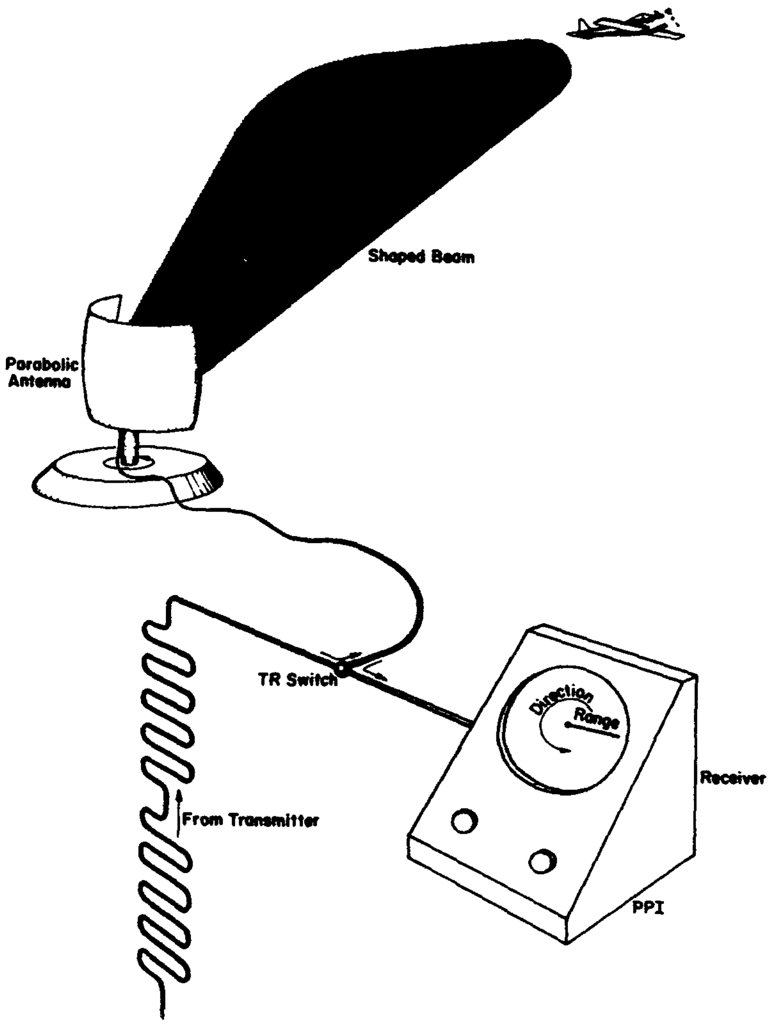
$$R = \frac{vt}{2}.$$

The factor of 2 arises because of the round-trip distance the signal must travel from the antenna to the target and then back. For ground radar in ice or any other dielectric material (conductors are far more complicated) the relationship is

$$R = \frac{vt}{2n}.$$

Since v and n are known for freshwater ice, R is simply related to t by

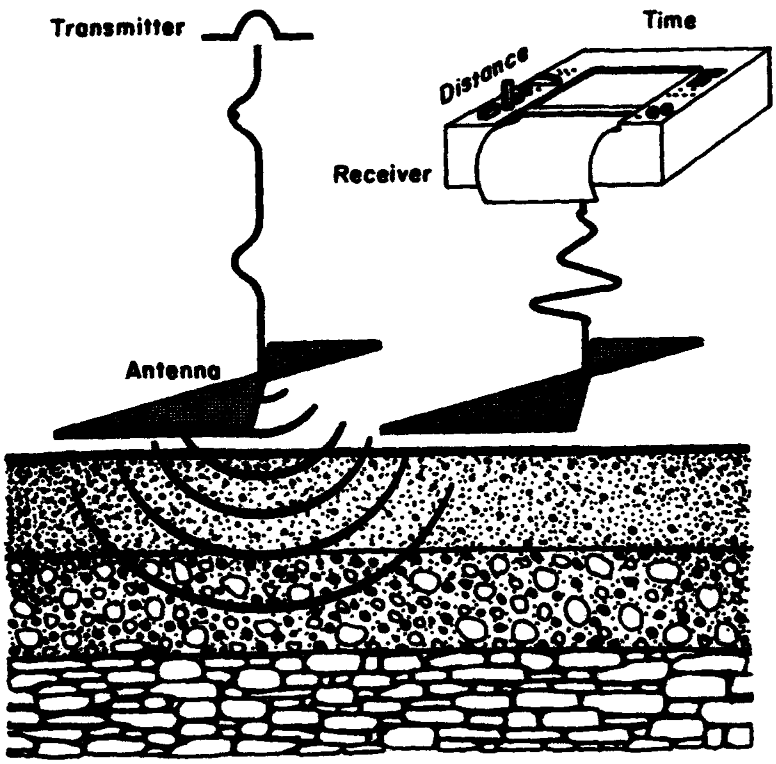
$$R\ (\text{cm}) = 8.33\ t\ (\text{ns}).$$



1. Simplified layout of conventional surveillance radar. Microsecond pulses of microwave energy (1-10 GHz) are propagated in a specially shaped beam formed by a large antenna. The echoes are displayed at their proper range on a CRT screen that is synchronized with antenna rotation, thus allowing direction to be displayed also.

The unit of nanoseconds (ns) may seem awesome in its brevity but is easily measurable with modern electronics.

Conventional radar uses the Plan Position Indicator (PPI) illustrated in Figure 1 for displaying target range and direction. A television type screen may display many targets at once as the antenna scans, due to the phosphorescence in the screen. In ground-probing radar, a linear profile is made where the horizontal axis is distance (i.e. antenna position as it is towed) and the vertical axis is echo time delay (Fig. 2). This profile is called a Z scan, and is actually a composite of thousands of echo scans, the intensity of which is indicated by the darkness of the print. Groups of bands represent a single return of several oscillations from a linear reflector. The display is the same as that on a fathometer in marine sonar systems.



2. Simplified layout of subsurface impulse radar. Nanosecond pulses of VHF-UHF (80-1000 MHz) energy are radiated in a wide beam by a broadband dipole type antenna. The echoes are received by a separate antenna and are displayed on a graphic recorder as the antennas are towed over the ground.

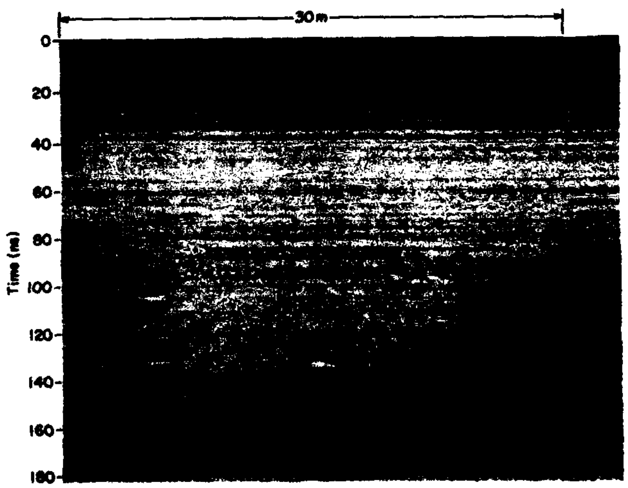
Radar profiling of ice

The important variables influencing radar propagation in ice are the electrical properties, the homogeneity and the smoothness of the ice cover. Cold freshwater ice has an index of refraction generally between 1.7 and 1.8 and is extremely non-conductive. When the ice temperature reaches 0 °C, however, as during spring thaw, water can infiltrate grain boundaries and significantly increase the bulk dielectric constant and conductivity. The factor n must then be determined with radar echoes obtained at known depths or by other means. Sea ice can range from a highly conductive medium during the first few months of formation, when bulk salinity is highest, to a fairly good dielectric (n between 2.2 and 1.8) medium late in winter, when much of the brine has drained. Late winter or early spring is then the best time to profile first-year sea ice. Multi-year ice is often of low salinity.

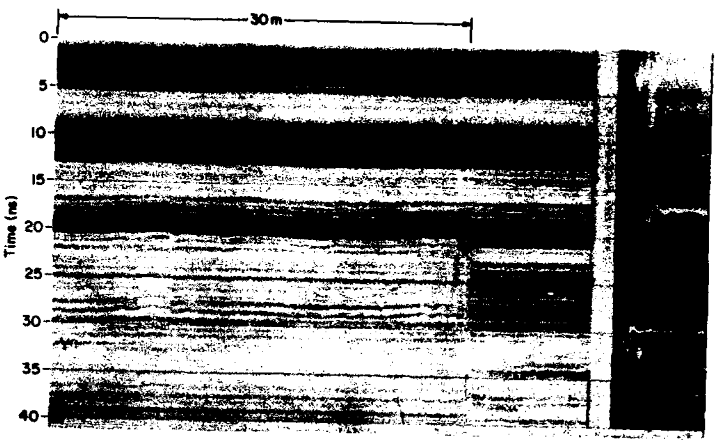
The thickness of an ice cover can exceed 2 m as is common in the Arctic. Such thicknesses are ideal for radar profiling because the returns from the ice/water interface will be clearly separated from the initial surface returns. Frazil ice covers may be so irregular that interpretation of the ice bottom contours may be difficult. In most cases, the high reflectivity of the ice/water interface and the usually conductive nature of some waters, especially sea water, preclude the possibility of any other events competing with echoes from the ice/water interface.

Some examples of ice cover profiles over lakes and rivers are shown in Figures 3–6. The examples in Figures 3, 4 and 6 are from my own work, while that in Figure 5 was done by Canadian researchers. The profiles were all made by hand-towing antennas over the ice cover. Different antennas were used in each survey and, when coupled with the ice, produced a pulse whose frequency spectrum was different in each case. However, the basic pulse waveforms transmitted were all similar and appeared like the received waveform shown in Figure 2, an initially large oscillation followed by a small decaying oscillation. When the system functions as desired, the data are no more interesting than would be a graph of ice thickness versus traverse distance. Therefore, there is only one example of perfect ice thickness detection (Fig. 4) and several examples illustrating complications.

Figure 3 illustrates the consequences of poor pulse length selection. The profiles are 30 m long and were made over several metres of water on Post Pond in Lyme, N.H., during late January when the ice thickness was 50 cm. Figure 3 was generated using an antenna that transmitted a pulse into the ice lasting about 10 ns with a bandwidth centered at about 220 MHz. In the ice, this gave a pulse length of about 170 cm, which was too long to allow the surface returns to separate from the bottom returns. Since the antenna is on the ice, the



3. Profile over a lake covered with 50 cm of ice. The pulse duration is too long to allow the bottom echo to separate from the surface echo. Sloping echoes are bottom reflections.



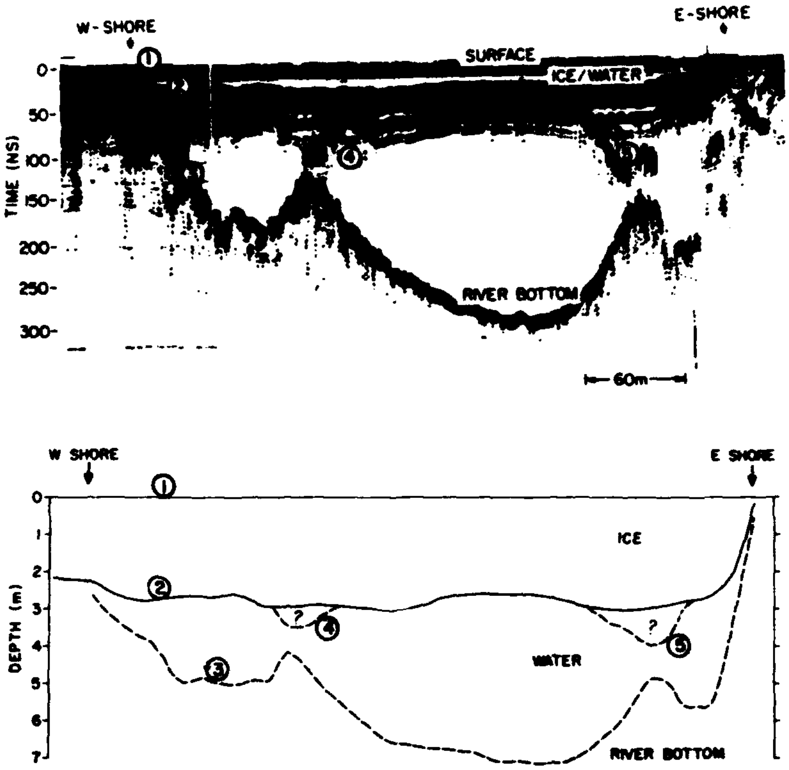
4. Profile of the same ice cover as in Figure 3 using a shorter duration pulse. The upper band is the direct air and surface reflection coupling between antennas. The second band is the ice bottom, and the third is a multiple reflection.

surface returns come in almost immediately and are the first set of darkest bands at the top. The more widely separated bands starting at about 14 ns are the ice bottom returns. The round trip flight time for a bottom echo here is only about 6 ns, so that for 8 ns these bottom echoes are intermeshed with the direct coupling and surface reflections. In addition, there are multiple reflections from the ice bottom, which explain the persistence of so many bands for up to 40 ns into the record. The sloping events at the bottom of the record are the lake bottom sediments.

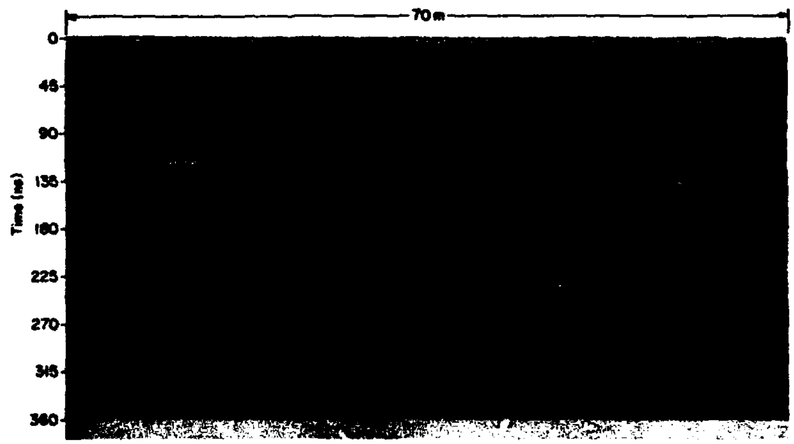
Figure 4 is a profile of the same ice cover made using a much smaller antenna that transmitted a pulse lasting about 3 ns with a bandwidth centered at about 700 MHz. This short duration allows the ice bottom reflections to be seen clearly. The third and latest event in Figure 4 is a second bottom echo or multiple reflection of energy that has bounced twice through the ice.

Figure 5 is a radar profile of an artificial ice bridge over the Yukon River made using a pulse whose frequency spectrum was centered near 100 MHz. The ice thickness here was as great as 3 m, which allowed such a low frequency to discriminate the ice bottom from the surface. Artificially made bridges of this type are usually not homogeneously dense and n will vary according to density. Consequently, we can see some variation within the ice cover as well as multiple reflections.

Figure 6 is a 70-m radar profile of the ice cover on Birch Lake near Delta Junction, Alaska, done in late April 1983. The radar pulse bandwith was centered at about 120 MHz. The ice cover was approximately 1 m thick and the index of



5. Radar section and interpretation of an ice bridge across the Yukon River obtained with 10-ns impulse antennas (after Annan and Davis 1977).



6. Radar profile of the ice cover on Birch Lake, Alaska. The cover was in a two-phase state and the inhomogeneities caused severe reflections (propagating modes) throughout the record.

refraction, as measured by other, independent wave propagation studies, was about 2.1 due to the two-phase nature of this 0°C ice cover. This combination of thickness and *n* precluded the possibility of seeing a bottom return separated from the direct surface transmissions.

Figure 6 does, however, demonstrate that two-phase ice covers can be extremely inhomogeneous, as evidenced by the numerous sloping returns. These are reflected modes dispersively propagating through the ice cover. They probably originate from zones of predominantly ice or water in any direction about the antenna. Their origins are generally obscured by the interface reflections but their presence verifies the fact that complex ice–water mixtures can exist over fresh water, making interpretation of a radar profile very difficult.

Radar profiling need not be confined to towing antennas over ice covers. Several efforts have been made to profile river ice floes, frazil ice, ice shelves, and multi-year sea ice using radar mounted under helicopters, on ships, and on booms hung from bridge abutments, or towed behind tracked or wheeled vehicles. Technically, radio echo sounding of glaciers, usually performed at 30 to 60 MHz and often from an aircraft, is also radar profiling of an ice cover.

Conclusion

Radar profiling of ice works best when the ice is solid, homogeneous and thicker than half the physical length of the pulse being transmitted divided by *n*. A subsurface radar antenna sacrifices gain (concentration of energy in a specific direction) to achieve an optimum temporal pulse shape. Therefore, antennas must be close to the ice surface to ensure that the return is from directly below the antenna and that power coupled into the ice will be sufficient for detection.

References

References 1–4 contain discussions of ground radar operation, although not all are concerned with ice cover profiling. Discussions of radar profiling of ice covers on freshwater lakes and rivers are given in 5–8; of sea ice in 2, 9 and 10; and of some related topics in 11–16. Work in the U.S.S.R. (with several references) is contained in a Draft Translation (17) prepared for the U.S. Army Cold Regions Research and Engineering Laboratory. In 1979 an entire conference (18) was devoted to the subject of sea ice profiling, and the proceedings contain 19 papers with further references.

1. **Morey, R.M.** (1974) Continuous subsurface profiling by impulse radar. *Proceedings of Engineering Foundation Conference on Subsurface Exploration for Underground Excavation and Heavy Construction,* American Society of Civil Engineers, pp. 213–232.
2. **Campbell, K.J. and A.S. Orange** (1974) The electrical anisotropy of sea ice in the horizontal plane. *Journal of Geophysical Research,* **79**(33): 5059–5063.
3. **Moffatt, D.L. and R.J. Puskar** (1976) A subsurface electromagnetic pulse radar. *Geophysics,* **41**(3): 506–518.
4. **Annan, A.P. and J.L. Davis** (1976) Impulse radar sounding in permafrost. *Radio Science,* **11**(4): 383–394.
5. **Kovacs, A. and R.M. Morey** (1978) Remote detection of water under ice-covered lakes on the North Slope of Alaska. *Arctic,* **31**(4): 448–458.
6. **Kovacs, A. and R.M. Morey** (1979) Remote detection of a freshwater pool off the Sagavanirktok River delta, Alaska. *Arctic,* **32**(2): 161–164.
7. **Annan, A.P. and J.L. Davis** (1977) Impulse radar applied to ice thickness measurement and freshwater bathymetry. Geological Survey of Canada Report of Activities, Part B, Paper 77-1B.
8. **Dean, A.M.** (1977) Remote sensing of accumulated frazil and brash ice in the St. Lawrence River. USA Cold Regions Research and Engineering Laboratory, CRREL Report 77-8.
9. **Campbell, K.J. and A.S. Orange** (1974) A continuous profile of sea ice and freshwater ice thickness by impulse radar. *Polar Record,* **17**: 31–41.
10. **Kovacs, A.** (1977) Sea ice thickness profiling and under-ice oil entrapment. *Proceedings of the 9th Annual Off-*

shore Technology Conference, Houston, Texas, preprint 2949.

11. **Kovacs, A. and A.J. Gow** (1975) Brine infiltration in the McMurdo Ice Shelf, McMurdo Sound, Antarctica. *Journal of Geophysical Research,* **80**(15): 1957–1961.
12. **Kovacs, A. and A.J. Gow** (1977) Subsurface measurements of the Ross Ice Shelf, McMurdo Sound, Antarctica. *Antarctic Journal of the U.S.,* **XII**(4): 146–148.
13. **Rossiter, J.R., P. Langhorne, T. Ridings and A.J. Allan** (1977) Study of sea ice using impulse radar. In *POAC 77: Proceedings, Fourth International Conference on Port and Ocean Engineering Under Arctic Conditions* (D.B. Muggeridge, Ed.), Memorial University of Newfoundland, St. John's, Newfoundland, Canada.
14. **Arcone, S.** (1981) Distortion of model subsurface radar impulses in complex dielectrics. *Radio Science,* **16**(5): 855–864.
15. **Sellmann, P.V., S.A. Arcone and A.J. Delaney** (1983) Radar profiling of buried reflectors and the groundwater table. USA Cold Regions Research and Engineering Laboratory, CRREL Report 83-11.
16. **Arcone, S.A.** (1984) Field observations of electromagnetic pulse propagation in dielectric slabs. *Geophysics,* **49**(10): 1763–1773.
17. **Finkel'shteyn, M.I. and E.I. Lazarev** (1981) A radar video pulse device for measuring the thickness of sea ice as a promising means of ice reconnaissance. USA Cold Regions Research and Engineering Laboratory, Draft Translation 758.
18. **Rossiter, J.R. and D.P. Bazely, Ed.** (1979) Proceedings of the International Workshop on the Remote Estimation of Sea Ice Thickness, St. John's, Newfoundland, Sept 25–26, 1979. C-CORE, Memorial University, Newfoundland, Canada, publication 80-5.